Magnesium-mediated Nucleophilic Borylation of Carbonyl Electrophiles

Anne-Frédérique Pécharman, Michael S. Hill,* Claire L. McMullin* and Mary F. Mahon

Department of Chemistry, University of Bath, Claverton Down, Bath, BA2 7AY, UK

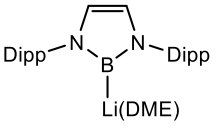
Email: msh27@bath.ac.uk

Abstract

The diboranate derivative, [HC{(Me)CNDipp}$_2$Mg{pinBB(nBu)pin}], resulting from treatment of a β-diketiminato magnesium n-butyl derivative with the commercially available diborane, B_2pin_2, reacts as a source of the [Bpin] nucleophile with ketones and organic isocyanates. Reactions with benzophenone and 9-fluorenone afford products which may be rationalized as enolate species resulting from kinetically controlled dearomatization rather than the thermodynamically preferred C-borylation of the electrophilic C=O unit provided by a previously described magnesium complex bearing a terminal [Bpin] nucleophile. The enolate derivatives react readily with further equivalents of the ketones to provide C-C coupling and tetra-alkoxyborate products via aldol condensation processes. In contrast to this divergent behaviour, reactions of isocyanates with [HC{(Me)CNDipp}$_2$Mg{pinBB(nBu)pin}] react similarly to the terminal boryl species to yield the anticipated C-boryl amidate products. Although we have yet to identify the origin of this contrasting reactivity, these results indicate the potential of these systems, which are ostensibly both sources of identical [Bpin] nucleophiles, to provide complementary but highly selective access to kinetic or thermodynamic reaction products.

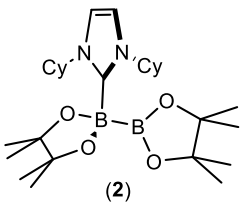
Introduction

Organic derivatives of trivalent boron (BR_3 or BAr_3) provide some of the prototypical neutral electrophiles and have, for example, played a central role in the development of Lewis acid- and 'frustrated' Lewis Pair (FLP)-based catalysis.[1-10] Organoboranes are similarly vital as intermediates in organic synthesis, either through simple oxidation or their application in Suzuki-Miyaura C-C cross coupling.[11-13] While the last 20 years have witnessed significant advances in, for example, the direct borylation of C-H bonds[14] and the development of increasingly specific or asymmetric hydroboration catalysis,[15, 16] a vast majority of methods for the installation of boron into organic molecules are dependent on the electrophilic character intrinsic to common boron halide or hydrido starting materials.

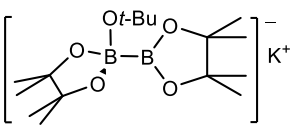


(**1**)

Dipp = 2,6-*i*-Pr$_2$C$_6$H$_3$

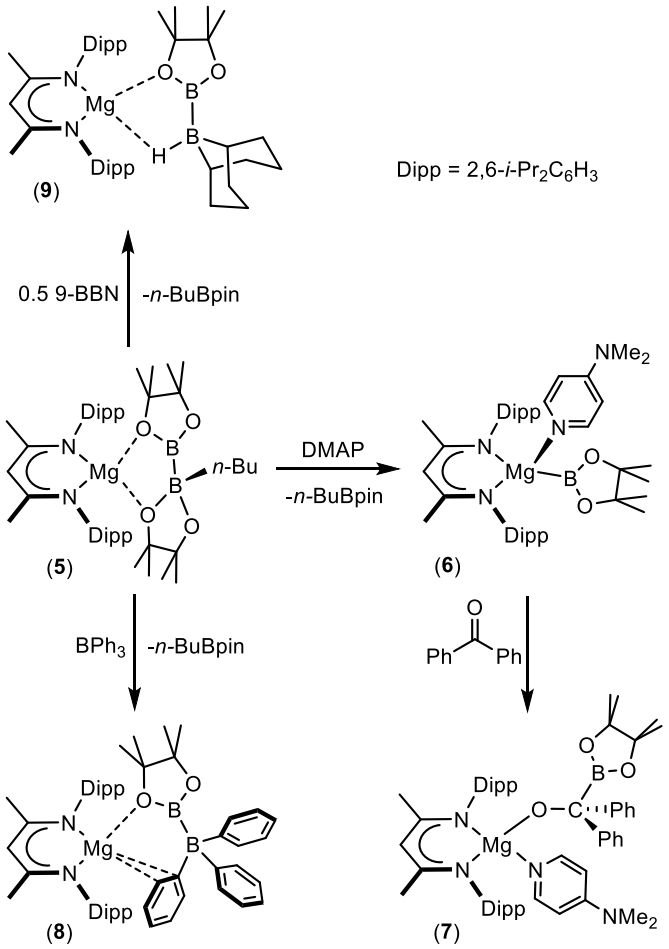


(**2**)



(**3**)

Irrespective of some similarly remarkable advances in the synthesis and uses of transition metal boryl derivatives,[12, 17, 18] Yamashita and Nozaki's report of the lithium boryl (**1**) was justly recognised as landmark in main group element synthesis.[19-23] While compound **1** has been shown to react with a wide range of organic and inorganic reagents as a source of an unambiguous boron-centered nucleophile,[24-32], in common with many of subsequently reported boron nucleophiles,[33-51] its synthesis requires inconvenient lithium reduction of a diamidohaloborane precursor. In parallel with these advances, therefore, reagents such as the neutral and anionic diborane adducts **2** and **3** have attracted attention as surrogates for boron nucleophiles.[52-61] In a similar manner, we have recently reported that magnesium diboranate species **5** are readily generated through reaction of the corresponding β-diketiminato *n*-butylmagnesium derivative [HC{(Me)CNDipp}$_2$Mg*n*Bu], **4**, Dipp = 2,6-*i*-Pr$_2$C$_6$H$_3$) with commercially available diboranes such as bis(pinacolato)diborane (Scheme 1). Subsequent treatment of **5** with 4-dimethylaminopyridine (DMAP) induced *n*-butylborane elimination to enable the convenient generation of derivatives such as **6**, which contains a terminal Mg-B bond.[62, 63] Compound **6** provides the [Bpin]$^-$ unit as a well behaved boron centered nucleophile when treated with both halogenated and non-halogenated organic electrophiles. Reaction with benzophenone, for example, provided B-C bond formation through attack at the electrophilic carbonyl carbon atom and generation of the unusual *C*-borylated alkoxide, **7** (Scheme 1).[63] We have also recently demonstrated the viability of compound **5** to behave as a source of the [Bpin]$^-$ nucleophile in its own right. In these cases, treatment with the boron-centered electrophiles, BPh$_3$ and 9-borabicyclo[3.3.1]nonane afforded compounds **8** and **9**, respectively, through facile B-B bond formation and elimination of *n*BuBpin.[64] In this contribution we extend our study of the attributes of compound **5** to act as an easily generated source of a [Bpin] nucleophile and report the outcome of its reactions with representative diaryl ketones and organoisocyanates.



Scheme 1: Synthesis of the terminal magnesium boryl (**6**) and magnesium-mediated activation of B_2pin_2 for the generation of nucleophilic $[Bpin]^-$ equivalents.

Experimental

General Experimental Procedures: All manipulations were carried out using standard Schlenk line and glovebox techniques under an inert atmosphere of argon. NMR experiments were conducted in J Young tap NMR tubes made up and sealed in a glovebox. NMR spectra were recorded on a Bruker AV300 spectrometer operating at 300.2 MHz (^{1}H), 75.5 MHz (^{13}C), 96.3 MHz (^{11}B) or an Agilent ProPulse spectrometer operating at 500 MHz (^{1}H), 126 MHz (^{13}C), 160.4 MHz (^{11}B). The spectra were referenced relative to residual solvent resonances or an external $BF_3.OEt_2$ standard (^{11}B). Solvents (toluene, hexane) were dried by passage through a commercially available (Innovative Technologies) solvent purification system, under nitrogen and stored in ampoules over molecular sieves. d_8-Toluene was purchased from Fluorochem Ltd. and Sigma-Aldrich Ltd. and dried over molten potassium before distilling under argon and storing over molecular sieves. Di-*n*-butylmagnesium (1.0 M solution in *n*-heptane) and B_2pin_2 were purchased from Sigma-Aldrich Ltd. Compound **4** was synthesized by a literature procedure.[65] Elemental analysis was carried out Mr Stephen Boyer of London Metropolitan Enterprises.

Compound 10. In a J Young NMR tube, toluene (0.5 mL) was added to a mixture of **4** (50 mg, 0.1 mmol) and B_2pin_2 (25.4 mg, 0.1 mmol). After 2 hours, 0.9 equivalents of benzophenone (16.4 mg, 0.09 mmol) were added. After a further 15 minutes, the solvent was removed under reduced pressure and hexane was added. Crystallization and recrystallization from the same solvent at room temperature provided compound **10** as colorless crystals suitable for X-ray diffraction analysis (25 mg, 37%). ^{1}H NMR (500 MHz, d_8-toluene) δ 7.42 (d, 2H, J_{HH} = 7.5 Hz, Ar-H), 7.21 (t, 2H, J_{HH} = 7.5 Hz, Ar-H), 7.11-6.99 (m, 7H, Ar-H), 6.43 (d, 1H, J_{HH} = 10.9 Hz, CH dearomatised cycle), 6.17 (d, 1H, J_{HH} = 10.9 Hz, CH dearomatised cycle), 5.95 (m, 1H, CH dearomatised cycle), 5.85 (m, 1H, CH dearomatised cycle), 5.04 (s, 1H, NC(CH_3)C*H*), 3.25 (m, 2H, C*H*(CH_3)$_2$), 2.95 (m, 2H, C*H*(CH_3)$_2$), 2.63 (s, 1H, B-C*H*-CH=CH), 1.73 (s, 3H,CH_3), 1.60 (s, 3H, CH_3), 1.38 (m, 3H, CH_3), 1.30-1.24 (m, 9H, CH_3), 1.15-1.14 (m, 3H, CH_3), 0.99 (m, 3H, CH_3), 0.91 (m, 3H, CH_3), 0.87 (m, 9H, CH_3), 0.57 (s, 6H, CH_3) ppm. ^{13}C{^{1}H} NMR (126 MHz, d_8-toluene) δ 171.29, 170.06, 145.03, 144.81, 144.31, 143.84, 142.34, 141.05, 140.85, 134.60, 132.86 (<u>C</u>H dearomatised cycle, HSQC with ^{1}H resonance at 6.17 ppm), 126.89 (CH ar), 125.67 (CH ar), 124.05 (<u>C</u>H dearomatised cycle, HSQC with ^{1}H resonance at 5.85 ppm), 123.14 (CH ar), 122.88 (CH ar), 122.50 (<u>C</u>H dearomatised cycle, HSQC with ^{1}H resonance at 5.95 ppm), 122.16, 121.12 (<u>C</u>H dearomatised cycle, HSQC with ^{1}H resonance at 6.42 ppm), 94.57 (NC(CH_3)<u>C</u>H), 79.59 (B(O<u>C</u>(CH_3)$_2$)$_2$), 31.65 (B-<u>C</u>H-CH=CH), 29.43 (<u>C</u>H(CH_3)$_2$), 29.12 (<u>C</u>H(CH_3)$_2$), 28.73 (<u>C</u>H(CH_3)$_2$), 27.97 (<u>C</u>H_3), 27.75 (<u>C</u>H_3), 27.27 (<u>C</u>H(CH_3)$_2$), 26.69 (<u>C</u>H_3), 25.39 (<u>C</u>H_3), 25.12 (<u>C</u>H_3), 24.97 (<u>C</u>H_3), 24.81 (<u>C</u>H_3), 24.68 (<u>C</u>H_3), 24.54 (<u>C</u>H_3), 24.50 (<u>C</u>H_3), 24.29 (<u>C</u>H_3), 24.22 (<u>C</u>H_3), 23.87 (<u>C</u>H_3), 23.32 (<u>C</u>H_3), 22.71 (<u>C</u>H_3) ppm. ^{11}B{^{1}H} NMR (160 MHz, d_8-toluene) δ 15.6 ppm.

Compound 11. In a J Young NMR tube, toluene (0.5 mL) was added to a mixture of **4** (20 mg, 0.04 mmol) and B_2pin_2 (10.7 mg, 0.04mmol). After 2 hours, 2 equivalents of benzophenone (14.6 mg, 0.08 mmol) were added. After a further 15 minutes, the solvent was removed under reduced pressure and the resultant solid was washed with hexane and dried under vacuum to yield compound **11** as a colorless powder (41 mg, 44%). Colorless crystals suitable for X-ray diffraction analysis were obtained from a saturated hexane solution at room temperature. ^{1}H NMR (300 MHz, d_8-toluene): δ 7.33 (m, 4H, Ar-*H*), 7.15 (m, 4H, Ar-*H*), 7.11 (m, 2H, Ar-*H*), 7.03 (s, 1H, Ar-*H*), 6.99 (br s, 1H), 6.96 (m, 2H, Ar-*H*), 6.94 (m, 2H, Ar-*H*), 6.81 (br s, 2H, Ar-*H*), 6.70 (br s, 4H, Ar-*H*), 6.55 (br s, 4H, Ar-*H*), 4.86 (s, 1H, NC(CH_3)C*H*), 3.87 (hept, 2H, J_{HH} = 6.8 Hz, C*H*(CH_3)$_2$), 2.95 (hept, 2H, J_{HH} = 6.8 Hz, C*H*(CH_3)$_2$), 1.70 (d, 6H, J_{HH} = 6.8 Hz, CH(CH_3)$_2$), 1.54 (s, 6H, NC(CH_3)CH), 1.51 (s, 12H, B(OC(CH_3)$_2$)$_2$),1.37 (s, 6H, J_{HH} = 6.8 Hz, CH(CH_3)$_2$), 0.97 (d, 6H, J_{HH} = 6.8 Hz, CH(CH_3)$_2$) ppm. ^{13}C{^{1}H} NMR (126 MHz, d_8-toluene) δ 170.15 (N<u>C</u>(CH_3)CH), 146.44, 143.83, 142.90, 137.06, 128.45(CH ar), 127.84(CH ar), 127.74, 127.73, 127.55, 127.54, 127.35, 127.34, 125.95 (CH ar), 125.77 (CH ar), 124.71, 124.66(CH ar), 124.51, 123.74 (CH ar), 122.88 (CH ar), 96.38 (NC(CH_3)<u>C</u>H), 79.27 (B(O<u>C</u>(CH_3)$_2$)$_2$), 27.97, 27.74 (<u>C</u>H(CH_3)$_2$), 27.63 (<u>C</u>H(CH_3)$_2$), 26.67 (B(OC(<u>C</u>H_3)$_2$)$_2$), 25.38 (CH(<u>C</u>H_3)$_2$), 25.33 (NC(<u>C</u>H_3)), 25.12 (CH(<u>C</u>H_3)$_2$), 24.49(CH(<u>C</u>H_3)$_2$), 24.30 (CH(<u>C</u>H_3)$_2$) ppm. ^{11}B{^{1}H} NMR (96 MHz, d_8-toluene): δ 10.3

ppm. Elemental analysis: Found C, 78.37; H, 7.99; N, 3.12 %. $C_{61}H_{73}BMgN_2O_4$ requires: C, 78.50; H, 7.88; N, 3.00 %.

Compound 12. In a J Young NMR tube, toluene (0.5 mL) was added to a mixture of **4** (50 mg, 0.1 mmol) and B_2pin_2 (25.4 mg, 0.1 mmol). After 2 hours at −35°C, 2 equivalents of 9-fluorenone (36.11 mg, 0.2 mmol) were added. Compound **12** crystallized after 14 hours at −35°C. The suspension was filtered, the solid was washed with hexane and dried under vacuum to afford compound **12** as a colorless solid (65.6 mg, 70 %). Colorless crystals suitable for X-ray diffraction analysis were obtained from a saturated hexane solution at room temperature. ^{1}H NMR (500 MHz, d_8-toluene) δ 7.33(d, 2H, Ar-*H*), 7.15-6.95 m(m, 4H, Ar-*H*), 6.76 (m, 16H, Ar-*H*), 4.82 (s, 1H, NC(CH_3)C*H*), 4.00 (m, 2H, C*H*(CH_3)$_2$), 2.42 (m, 2H, C*H*(CH_3)$_2$), 1.91 (d, 6H, C*H*$_3$), 1.54 (m, 12H, C*H*$_3$), 1.36 (d, 6H, C*H*$_3$), 1.19 (m, 6H, C*H*$_3$), 0.92 (d, 6H, C*H*$_3$), 0.39 (s, 6H, C*H*$_3$) ppm. ^{13}C{^{1}H} NMR (126 MHz, d_8-toluene) δ 168.71 (N*C*(CH_3)CH), 167.09 (N*C*(CH_3)CH), 147.61, 147.32, 146.42, 143.46, 142.32, 141.82, 135.90, 133.96, 123.87 (CH ar), 123.78 (CH ar), 123.57 (CH ar), 123.22 (CH ar), 122.88 (CH ar), 122.84 (CH ar), 120.25, 96.36 (NC(CH_3)*C*H), 81.19 (B(O*C*(CH_3)$_2$)$_2$), 28.52 (*C*H$_3$), 27.97 (*C*H(CH_3)$_2$), 26.17 (*C*H$_3$), 26.03 (*C*H$_3$), 24.85 (*C*H$_3$), 24.77 (*C*H$_3$), 24.45 (*C*H$_3$), 24.08 (*C*H$_3$), 23.51 (*C*H$_3$), 23.31 (*C*H$_3$), 22.96 (*C*H$_3$), 22.87 (*C*H$_3$), 22.69 (*C*H$_3$) ppm. ^{11}B{^{1}H} NMR (160 MHz, d_8-toluene) δ 11.2 ppm. Elemental analysis: Found C, 78.69; H, 7.60 N, 3.16 %. $C_{61}H_{69}BMgN_2O_4$ requires: C, 78.84; H, 7.48; N, 3.01 %.

Compound 13. In a J Young NMR tube, toluene (0.5 mL) was added to a mixture of **4** (50 mg, 0.1 mmol) and B_2pin_2 (25.4 mg, 0.1 mmol). After 2 hours, *tert*-butylisocyanate (9.93 mg, 0.1 mmol) was added. After a further 2 hours, the solvent was removed under reduced pressure and the resultant colorless solid was washed with hexane and dried under vacuum to afford compound **13** (30 mg, 52%). Colorless crystals suitable for X-ray diffraction analysis were obtained from a saturated hexane solution of **13** at −35˚C. ^{1}H NMR (300 MHz, d_8-toluene): δ 7.12 (m, 6H, Ar-*H*), 5.01 (s, 1H, NC(CH_3)C*H*), 3.38 (m, 4H, C*H*(CH_3)$_2$), , 1.68 (s, 6H, NC(C*H*$_3$)CH), 1.52 (s, 9 + 6H, NC(C*H*$_3$)$_3$ + CH(C*H*$_3$)$_2$), 1.29 (br s, 12H, B(OC(C*H*$_3$)$_2$)$_2$), 1.22 (br d, 6H, CH(C*H*$_3$)2), 1.13 (br s, 6H, CH(C*H*$_3$)$_2$) ppm. ^{13}C{^{1}H} NMR (75 MHz, d_8-toluene): δ 170.41 (N*C*(CH_3)CH), 144.16 (*C*$_{ipso}$), 142.52 (*C*$_{ortho}$), 126.04 (*C*$_{para}$), 124.54 (*C*$_{meta}$), 98.64 (NC(CH_3)*C*H), 83.80 (B(O*C*(CH_3)$_2$)$_2$), 52.30 (N*C*(CH_3)$_3$), 31.56 (NC(*C*H$_3$)$_3$), 28.95, 28.53, 25.80, 25.68 (B(OC(*C*H$_3$)$_2$)$_2$), (CH(*C*H$_3$)$_2$), (*C*H(CH_3)$_2$), (CH(*C*H$_3$)$_2$) ppm. ^{11}B{^{1}H} NMR (96 MHz, d_8-toluene): δ 6.1 ppm. Elemental analysis: Found C, 72.03; H, 9.40; N, 6.22 %. $C_{80}H_{124}B_2Mg_2N_6O_6$ requires: C, 71.91; H, 9.35; N, 6.29 %.

Compound 14. In a J Young NMR tube, toluene (0.5 mL) was added to a mixture of **4** (50 mg, 0.1 mmol) and B_2pin_2 (25.4 mg, 0.1 mmol). After 2 hours, 2,6-di-*iso*propylphenylisocyanate (8.56 μL, 0.1 mmol) was added. After a further 2 hours, the solvent was removed under reduced pressure and the

solid was washed with hexane and dried to afford compound **14** as a colorless solid (45 mg, 63%). Colorless crystals suitable for X-ray diffraction analysis were obtained from a saturated hexane solution at room temperature. ^{1}H NMR (500 MHz, d_8-toluene) δ 7.20 (m, 3H, aromatic C*H*), 7.10 (m, 2H, aromatic C*H*), 6.93 (m, 4H, aromatic C*H*), 4.97 (s, 1H, (NC(CH_3)C*H*) , 3.64 (m, 2H, C*H*(CH_3)$_2$), 3.24 (m, 2H, C*H*(CH_3)$_2$), 2.34 (m, 2H, C*H*(CH_3)$_2$), 1.69 (s, 6H, CH_3), 1.47 (br s, 6H, CH_3), 1.27 (m, 24H, 8 x CH_3), 0.76 (s, 12H, B(OC(C*H*$_3$)$_2$)$_2$), 0.68 (d, 6H, CH_3) ppm. ^{13}C{^{1}H} NMR (126 MHz, d_8-toluene) δ 169.41 (N*C*(CH_3)CH), 144.43, 144.11, 140.07, 125.42 (aromatic CH), 123.69 (aromatic CH), 122.88 (aromatic CH), 122.35 (aromatic CH), 94.66 (NC(CH_3)*C*H), 83.49 (B(O*C*(CH_3)$_2$)$_2$), 27.97 (*C*H(CH_3)$_2$), 27.79 (*C*H(CH_3)$_2$), 27.55 (*C*H(CH_3)$_2$), 24.80 (CH_3), 23.95 (CH_3), 23.80 (CH_3), 23.62 (CH_3) ppm. Elemental analysis: Found C, 74.55; H, 9.28; N, 5.54 %. $C_{48}H_{70}BMgN_3O_3$ requires: C, 74.66; H, 9.14; N, 5.44 %.

Results and Discussion

Reaction of compound **5**, generated *in situ* by addition of B_2pin_2 to compound **4**, with 0.9 equivalents of benzophenone provided immediate consumption of the ketone starting material. Inspection of the resultant ^{1}H NMR spectrum indicated that this procedure had resulted in a single predominant reaction product, compound **10**, which had formed alongside a further minor component, compound **11**, in an approximate 4:1 ratio while leaving a small amount of compound **5** unreacted. Repetition of this reaction confirmed the validity of this result, albeit with minor variations of the relative proportions of compounds **10** and **11** produced. Compound **10** displayed 4 characteristic and mutually coupled alkenic resonances in its ^{1}H NMR spectrum between 5.85 and 6.43 ppm, which appeared alongside a broad singlet signal at δ 2.63 ppm. All of these signals displayed the same intensity, resonating as single protons by integration relative to the 1H signal of the β-diketiminate methine proton at δ 5.04 ppm. Further experiments revealed that compound **10** could be cleanly converted to compound **11**, leading to the complete disappearance of the apparent alkenic resonances, by addition of a further equivalent of benzophenone. Alternatively, compound **11** could be generated completely specifically from the reaction of compound **5** with two molar equivalents of benzophenone. Despite the contrasting ^{1}H NMR spectra, both compounds **10** and **11** displayed similarly broad resonances in their respective ^{11}B{^{1}H} NMR spectra at chemical shifts (**10**: δ 15.6; **11**: 10.3 ppm) consistent with the presence of 4-coordinate boron, which appeared alongside the significantly deshielded resonance of *n*-BuBpin at δ 34.3 ppm, irrespective of the reaction stoichiometry. The origin of these observations was resolved through the isolation of samples of compounds **10** and **11** from hexane solutions at room temperature, which were suitable for X-ray diffraction analysis. The results of these analyses are shown in Figure 1 while selected bond length and angle data are presented in the figure caption.

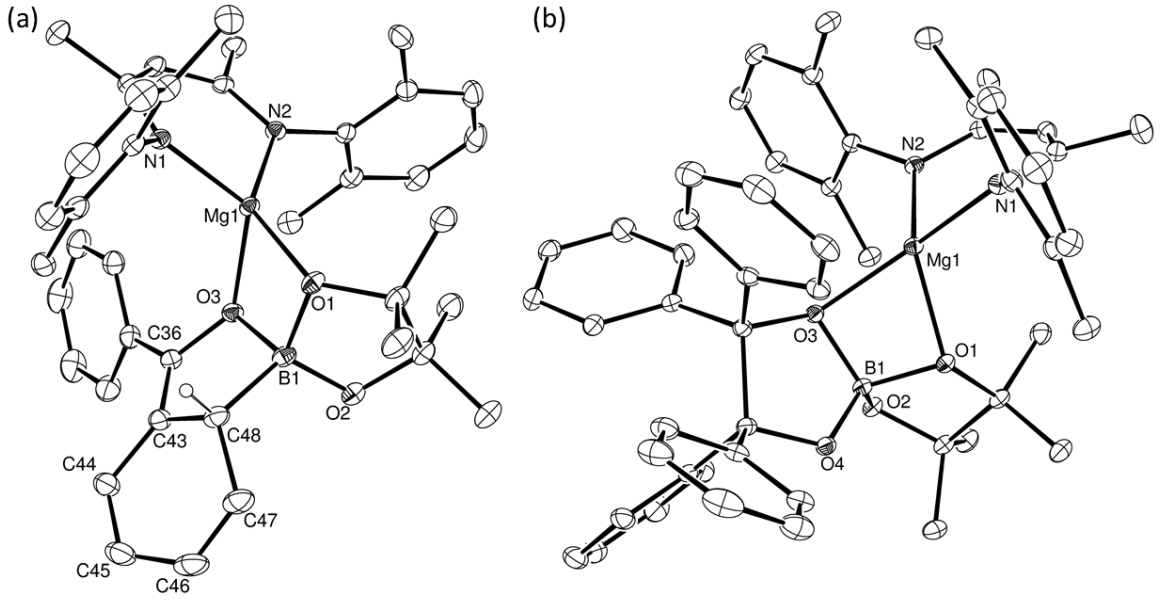
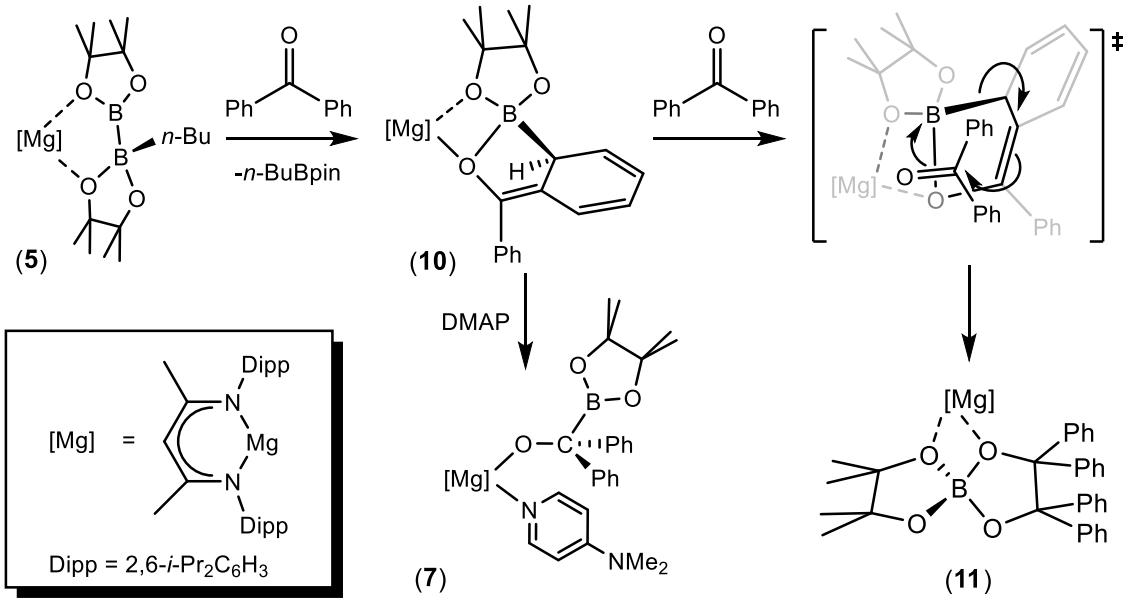


Figure 1: ORTEP representations (25% probability ellipsoids) of (a) compound **10** and (b) compound **11**. Hydrogen atoms, except the hydrogen attached to C48 of compound **10**, the methyl groups of the *iso*-propyl substituents and half a molecule of hexane solvent, which co-crystallized with compound **10**, have been omitted for clarity. Selected bond lengths (Å) and angles (°): (**10**) Mg1-N1 2.0375(14), Mg1-N2 2.0310(14), Mg1-O1 1.9967(12), Mg1-O3 1.9881(12), O1-B1 1.511(2), O2-B1 1.423(2), O3-B1 1.588(2), C48-B1 1.626(3), C36-C43 1.348(2), C43-C44, 1.444(3), C44-C45 1.345(3), C45-C46 1.445(4), C46-C47 1.336(3), C47-C48 1.502(2), O1-Mg1-N1 121.26(5), O1-Mg1-N2 134.43(6), O1-Mg1-B1 34.65(5), O3-Mg1-O1 71.41(5), O3-Mg1-N1 122.81(6), O3-Mg1-N2 113.50(5), O3-Mg1-B1 36.83(5), O1-B1-O3 97.22(12), O1-B1-C48 122.44(14), O2-B1-O1 105.10(15), O2-B1-O3 117.50(14), O2-B1-C48 114.86(14); (**11**) Mg1-O1 2.0464(9), Mg1-O3 2.0551(9), Mg1-N1 2.0667(11), Mg1-N2 2.0765(11), O1-B1 1.5154(16), O2-B1 1.4331(16), O3-B1 1.5017(15), O4-C49 1.4102(15), O4-B1 1.4375(16), O1-Mg1-O3 70.63(3), O1-Mg1-N1 109.14(4), O1-Mg1-N2 127.23(4), O3-Mg1-N1 154.66(4), O3-Mg1-N2 105.53(4), N1-Mg1-N2 94.60(4), O2-B1-O1 102.86(10), O2-B1-O3 114.95(10), O2-B1-O4 117.43(10), O3-B1-O1 103.60(9), O4-B1-O1 113.71(10), O4-B1-O3 103.75(10).

Compound **10** may be rationalized as the result of addition of a [Bpin] nucleophile provided by compound **5** to a single equivalent of benzophenone, which has occurred with the formal loss of *n*-BuBpin. In contrast to the previously reported compound **7**, which resulted from similar treatment of the terminal boryl species **6** with Ph_2CO, but consistent with observations provided by the solution NMR spectra, the formation of the new B-C bond has not taken place at the former carbonyl carbon atom. Rather, the now four-coordinate pinacolatoboron center is bonded through both the oxygen and an *ortho*-carbon atom (C48) of one of the phenyl substituents of the otherwise intact benzophenone skeleton. The apparent nucleophilic addition of a [Bpin] unit at this position has resulted in

dearomatization such that the C_6 carbocycle displays alternating long [C43-C44, 1.444(3); C45-C46, 1.445(4) C47-C48, 1.502(2) Å] and short [C44-C45, 1.345(3); C46-C47, 1.336(3) Å] C-C bonds consistent with its formulation as a cyclic diene. Although, as a result of the dearomatization process, the former (C36) carbonyl carbon center retains its planar sp^2 hydbridization state, the C36-C43 [1.348(2) Å] and C36-C37 [1.4682(2) Å] bond lengths indicate that the resultant anion is best considered as a boron-substituted, magnesium enolate (Scheme 2). From this perspective we suggest that the production of compound **11**, comprising what may be considered as a β-diketiminato magnesium tetraalkoxyborate species, is best rationalized as the result of a facile aldol-type C-C coupling process resulting from enolate attack at the electrophilic carbon center of a second equivalent of benzophenone (Scheme 2).



Scheme 2: Synthesis of compounds **10** and **11**.

We have not yet been able to obtain any experimental evidence for the mechanism through which *n*-BuBpin is displaced during the reaction of **5** and benzophenone. The resultant dearomatized enolate anion of compound **10**, however, was identified as the kinetic product of this transformation by density functional theory (DFT) calculations. Although the dearomatized enolate isomer (**10**) lies some 2.5 kcal mol^{-1} higher in free energy than the alternative borylalkoxide in which B-C bond formation occurs by addition of the [Bpin] unit to the carbonyl carbon atom of the benzophenone, isolated samples of compound **10** were found to be indefinitely stable in C_6D_6 solution at ambient temperature. This deduction was underscored by addition of DMAP, which led to immediate isomerization of the enolate anion to yield the previously reported derivative **7**, a process which was calculated to be significantly exergonic (Scheme 2, ΔG = −18.4 kcal mol^{-1}). Consistent with the synthetic observations, the transformation of compound **5** to the borate **11**, via the intermediacy of compound **10**, was calculated

to be thermodynamically spontaneous ($\Delta G = -56.2$ kcal mol^{-1}) in a process which we suggest is driven by phenyl rearomatization and the intrinsic strength of the new B-O bonds. Support for this latter observation was provided by a further reaction of compound **5** which was performed with a stoichiometric quantity of 9-fluorenone. In this case addition of the ketone at −35°C resulted in the consumption of only 50% of the diboranate starting material, which persisted in solution alongside a single new compound (**12**). Complete conversion to compound **12** could, however, be achieved through addition of a second equivalent of 9-fluorenone or repetition of the reaction with a 1:2 ratio of the magnesium and ketone reagents. After removal of volatiles and washing with a minimal amount of hexane to remove *n*-BuBpin, a sample of **12** suitable for single crystal X-ray analysis was isolated by crystallization from a saturated hexane solution. The outcome of this analysis (Figure 2) confirmed the structure of **12** as a magnesium tetraalkoxyborate species analogous to **11** in which the former carbonyl carbon centers of two equivalents of 9-fluorenone have undergone a C-C coupling process. Both benzophenone and 9-fluorenone have long been known to undergo reductive pinacol coupling of the relevant ketyls to provide the symmetrically substituted 1,2-diolates.[66, 67] Although we are not able to completely discount the possibility that a radical mechanism is implicated in the generation of either compound **11** or **12**, we have not yet observed evidence that species such as **5** and **6** undergo any single electron transfer reactivity which would be a necessary attribute of a radical-based process. The identification of compound **10** as an intermediate *en route* to **11**, therefore, leads us to suggest that a similar mechanism, analogous to that depicted in Scheme 2 for the production of compound **11**, is operant during the generation of both compounds. DFT calculations confirmed that the transformation of **5** to **12** is highly exergonic ($\Delta G = -62.3$ kcal mol^{-1}). We suggest that the direct generation of compound **12** observed with 50% consumption of the diboranate starting material during the stoichiometric reaction of **5** and 9-fluorenone, thus, reflects the higher degree of aromatic disruption necessary to form an unobserved dearomatized enolate intermediate analogous to compound **10**.

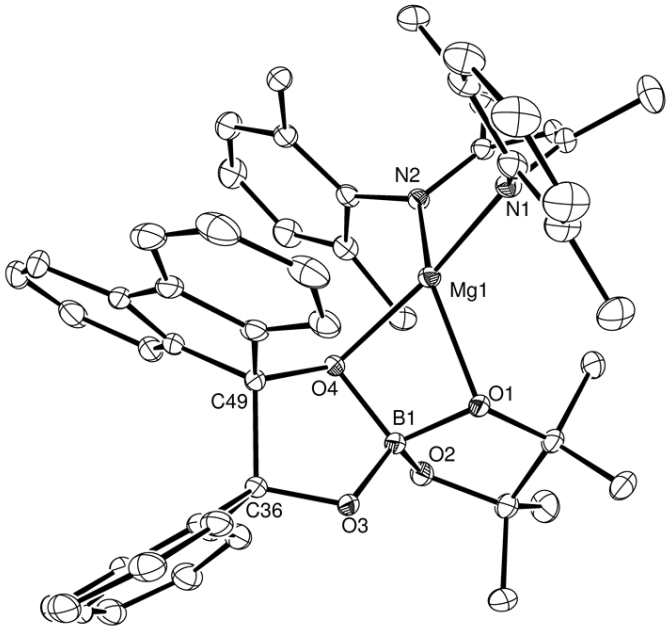
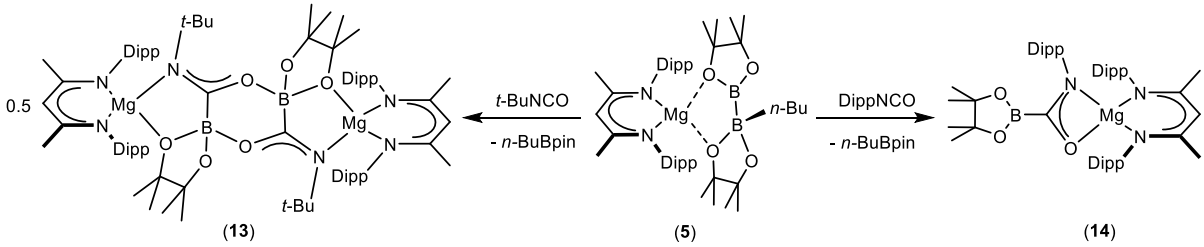


Figure 2: ORTEP representation of compound **12**. Hydrogen atoms and methyl groups of the *iso*-propyl substituents have been removed for clarity. Selected bond lengths (Å) and angles (°): Mg1-O1 2.0837(14), Mg1-O4 2.0432(14), Mg1-N1 2.0624(17), Mg1-N2 2.0541(17), O1-B1 1.507(3), O2-B1 1.428(3), O3-B1 1.449(3), O4-B1 1.510(2), O1-Mg1-B1 35.37(6), O4-Mg1-O1 70.59(5), O4-Mg1-N1 161.60(7), O4-Mg1-N2 98.55(6), N1-Mg1-O1 109.93(7), N2-Mg1-O1 132.32(7), N2-Mg1-N1 94.14(7), O1-B1-O4 104.43(14), O2-B1-O1 103.62(15), O2-B1-O3 118.32(17), O2-B1-O4 112.48(17), O3-B1-O1 113.38(17), O3-B1-O4 103.98(15).

We have previously reported that addition of the heterocumulene, *i*-PrN=C=N*i*-Pr, to compound **6** resulted in smooth borylation of the electrophilic linear carbodiimide carbon center.[62] Although reactions of compound **5** with carbodiimide substrates will be decribed elsewhere, reactions of equimolar quantities of isoelectronic alkyl and aryl isocyanates provided similar observations. Addition of either *t*-BuNCO or DippNCO, resulted in the immediate production of *n*-BuBpin [$\delta(^{11}B) = 34.3$ ppm] and the exclusive production of two new β-diketiminato magnesium derivatives, compounds **13** and **14**, respectively (Scheme 3).



Scheme 3: Synthesis of compounds **13** and **14**.

In both cases, crystallization from hexane yielded crystals suitable for single crystal X-ray analysis (Figure 3), which, irrespective of the *N*-alkyl or –aryl substitution of the isocyanate, demonstrated that completely selective formation of the respective *C*-borylated amidates had been achieved. Although a variety of related magnesium amidate derivatives have been described,[68-71] the formulation of the *C*-borylated amidate ligands appears to be unique. Compound **13**, derived from *t*-BuNCO, is a non-centrosymmetric dimer in which each of the two 4-coordinate magnesium centers are similarly bound by single, chelating β-diketiminate and *C*-borylated amidate ligands and the two halves of the dimer are otherwise identical. Dimer propagation occurs through B-O bonds formed between the previously terminal isocyanate oxygen atoms and the now 4-coordinate B1 and B2 boron centers, such that the various B-O bond lengths allow a definitive discrimination between inter- [B1-O4 1.530(4), B2-O3 1.527(4) Å] and intramolecular [B1-O1 1.497(4), B1-O2 1.434(4); B2-O5 1.435(4), B2-O6 1.495(4) Å] B-O-C linkages.

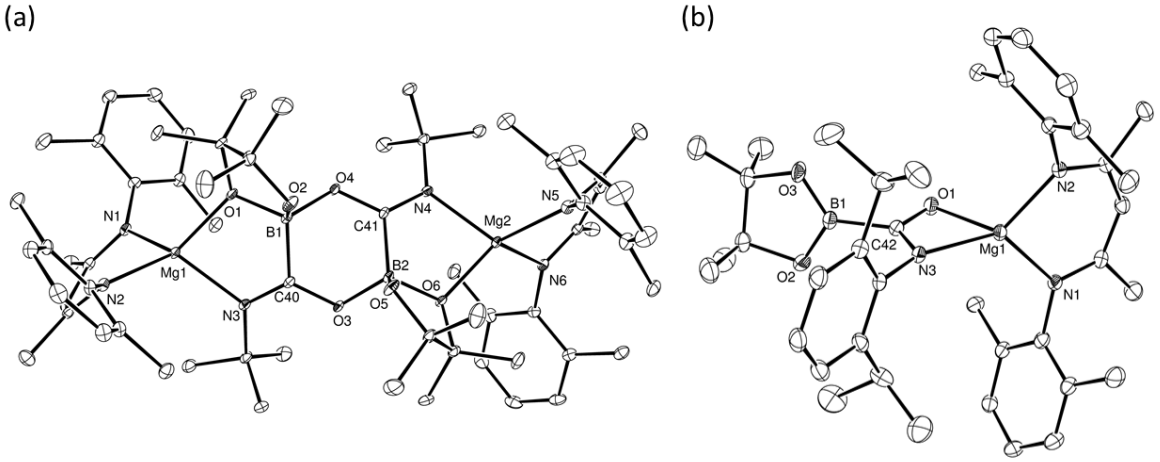


Figure 3: ORTEP representations of the structures of compound **13** and the Mg1-containing molecule of compound **14**. Hydrogen atoms, methyl groups of β-diketiminate *iso*propyl substituents, disordered atoms and disordered atoms of occluded solvent have been removed for clarity. Selected bond lengths (Å) and angles (°): (**13**) N1-Mg1 2.069(3), N2-Mg1 2.108(3), N3-Mg1 2.115(3), O1-Mg1 2.009(2), C40-N3 1.304(4), C40-O3 1.328(4), C40-B1 1.638(4), O1-B1 1.497(4), O2-B1 1.434(4), O4-B1 1.530(4), N1-Mg1-N2 90.17(10), N1-Mg1-N3 126.53(11), N2-Mg1-N3 117.13(11), O1-Mg1-N1 111.68(10), O1-Mg1-N2 132.99(11), O1-Mg1-N3 83.32(10), O1-B1-C40 107.2(3), O1-B1-O4 110.7(2), O2-B1-C40 121.2(3), O2-B1-O1 104.5(2), O2-B1-O4 109.0(3), O4-B1-C40 104.1(2); (**14**) Mg1-O1 1.999(2), Mg1-N1 2.029(3), Mg1-N2 2.028(3), Mg1-N3 2.105(2), O1-C42 1.289(3), N3-C42 1.313(4), C42-B1 1.601(4), O2-B1 1.351(4), O3-B1 1.348(3), O1-Mg1-N1 116.77(13), O1-Mg1-N2 116.45(13), O1-Mg1-N3 65.75(8), N1-Mg1-N3 129.84(14), N2-Mg1-N1 96.34(9), N2-Mg1-N3 128.92(14), C42-O1-Mg1 90.72(16), C42-N3-Mg1 85.54(16), O1-C42-N3 118.0(2), O1-C42-B1 114.7(2), N3-C42-B1 127.3(2).

In contrast to the dimeric constitution of **13**, and although solution and refinement were hampered by ambiguous crystal symmetry, compound **14** adopts a monomeric structure in the solid state which is undoubtedly a result of the greater steric demands of the *N*-Dipp substituent of the amidate ligand. The coordination spheres of the magnesium centers of both independent molecules in the monoclinic unit cell are, thus, provided by the β-diketiminate ligands and the bidentate amidate anions, which coordinate in a κ^2-fashion through each of the possible *N*- and *O*-donor interactions. The imposition of a monomeric structure in the case of **14**, however, ensures that each of the four unique boron centers retain the *pseudo*-trigonal planar geometry of the B_2pin_2 starting material. The change in the amidate ligand binding mode and the higher coordinate geometry of the boron centers of the dimeric molecule result in significant variations across the comparable C-B, C-N and C-O distances of both compounds **13** and **14**.

Conclusion

In summary, we report that a diboranate derivative (**5**), resulting from treatment of a kinetically stabilized magnesium alkyl (**4**) with the commercially available B_2pin_2, provides a source of the [Bpin] nucleophile which react spontaneously with aromatic ketones and organic isocyanates. In behaviour reminiscent of the previously reported reactivity of the terminal magnesium boryl (**6**) with isoelectronic heterocumulenes, compound **5** reacts with isocyanates to provide the anticipated *C*-boryl amidates. In contrast, reactions of compound **5** with diaryl ketones afford kinetically determined reaction products which may be identified as a result of enolate dearomatization rather than the thermodynamically preferred *C*-borylation of the electrophilic C=O unit provided by **6**. Although we have yet to identify the origin of this contrasting reactivity, these results indicate the potential of these systems, which are ostensibly both sources of identical [Bpin] nucleophiles, to provide divergent and highly selective access to kinetic or thermodynamic reaction products.

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: XXX
CCDC XXX−XXX contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

Notes

The authors declare no competing financial interest.

Acknowledgements

The EPSRC (UK) are acknowledged for financial support under awards EP/R020752/1 and EP/N014456/1.

References

1. Parks, D. J.; Blackwell, J. M.; Piers, W. E. *J. Org. Chem.* **2000,** *65*, 3090-3098.
2. Parks, D. J.; Piers, W. E.; Parvez, M.; Atencio, R.; Zaworotko, M. J. *Organometallics* **1998,** *17*, 1369-1377.
3. Parks, D. J.; Piers, W. E.; Yap, G. P. A. *Organometallics* **1998,** *17*, 5492-5503.
4. Parks, D. J.; Piers, W. E. *J. Am. Chem. Soc.* **1996,** *118*, 9440-9441.
5. Parks, D. J.; Spence, R.; Piers, W. E. *Angew. Chem., Int. Ed.* **1995,** *34*, 809-811.
6. Stephan, D. W.; Erker, G. *Angew. Chem., Int. Ed.* **2010,** *49*, 46-76.
7. Stephan, D. W. *Frustrated Lewis Pairs I: Uncovering and Understanding* **2013,** *332*, 1-44.
8. Stephan, D. W. *Science* **2016,** *354*, 1248.
9. Fontaine, F. G.; Stephan, D. W. *Philos. Transactions Roy. Soc. a-Math.l Phys. Eng. Sci.* **2017,** *375*.
10. Fasano, V.; Ingleson, M. J. *Synthesis-Stuttgart* **2018,** *50*, 1783-1795.
11. Suzuki, A. *Angew. Chem., Int. Ed.* **2011,** *50*, 6722-6737.
12. Dang, L.; Lin, Z. Y.; Marder, T. B. *Chem. Commun.* **2009**, 3987-3995.
13. Hartwig, J. F. *Acc. Chem. Res.* **2012,** *45*, 864-873.
14. Mkhalid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. *Chem. Rev.* **2010,** *110*, 890-931.
15. Obligacion, J. V.; Chirik, P. J. *Nature Rev. Chem.* **2018,** *2*, 15-34.
16. Kaur, P.; Khatik, G. L.; Nayak, S. K. *Current Org. Synth.* **2017,** *14*, 665-682.
17. Irvine, G. J.; Lesley, M. J. G.; Marder, T. B.; Norman, N. C.; Rice, C. R.; Robins, E. G.; Roper, W. R.; Whittell, G. R.; Wright, L. J. *Chem. Rev.* **1998,** *98*, 2685-2722.
18. Kays, D. L.; Aldridge, S. In *Contemporary Metal Boron Chemistry I: Borylenes, Boryls, Borane*, Marder, T. B.; Lin, Z., Eds. **2008**; Vol. 130, pp 29-122.
19. Segawa, Y.; Yamashita, M.; Nozaki, K. *Science* **2006,** *314*, 113-115.
20. Marder, T. B. *Science* **2006,** *314*, 69-70.
21. Segawa, Y.; Suzuki, Y.; Yamashita, M.; Nozaki, K. *J. Am. Chem. Soc.* **2008,** *130*, 16069-16079.
22. Yamashita, M.; Nozaki, K. In *Synthesis and Application of Organoboron Compounds*, Fernandez, E.; Whiting, A., Eds. **2015**; Vol. 49, pp 1-37.
23. Braunschweig, H. *Angew. Chem., Int. Ed.* **2007,** *46*, 1946-1948.
24. Yamashita, M.; Suzuki, Y.; Segawa, Y.; Nozaki, K. *J. Am. Chem. Soc.* **2007,** *129*, 9570-+.
25. Segawa, Y.; Yamashita, M.; Nozaki, K. *Angew. Chem., Int. Ed.* **2007,** *46*, 6710-6713.
26. Terabayashi, T.; Kajiwara, T.; Yamashita, M.; Nozaki, K. *J. Am. Chem. Soc.* **2009,** *131*, 14162.

27. Arnold, T.; Braunschweig, H.; Ewing, W. C.; Kramer, T.; Mies, J.; Schuster, J. K. *Chem. Commun.* **2015,** *51*, 737-740.
28. Protchenko, A. V.; Birjkumar, K. H.; Dange, D.; Schwarz, A. D.; Vidovic, D.; Jones, C.; Kaltsoyannis, N.; Mountford, P.; Aldridge, S. *J. Am. Chem. Soc.* **2012,** *134*, 6500-6503.
29. Protchenko, A. V.; Dange, D.; Harmer, J. R.; Tang, C. Y.; Schwarz, A. D.; Kelly, M. J.; Phillips, N.; Tirfoin, R.; Birjkumar, K. H.; Jones, C.; Kaltsoyannis, N.; Mountford, P.; Aldridge, S. *Nature Chem.* **2014,** *6*, 315-319.
30. Dange, D.; Davey, A.; Abdalla, J. A. B.; Aldridge, S.; Jones, C. *Chem. Commun.* **2015,** *51*, 7128-7131.
31. Campos, J.; Aldridge, S. *Angew. Chem., Int. Ed.* **2015,** *54*, 14159-14163.
32. Frank, R.; Howell, J.; Campos, J.; Tirfoin, R.; Phillips, N.; Zahn, S.; Mingos, D. M. P.; Aldridge, S. *Angew. Chem., Int. Ed.* **2015,** *54*, 9586-9590.
33. Okuno, Y.; Yamashita, M.; Nozaki, K. *Angew. Chem., Int. Ed.* **2011,** *50*, 920-923.
34. Wang, B. L.; Li, Y. X.; Ganguly, R.; Hirao, H.; Kinjo, R. *Nature Commun.* **2016,** *7*, 11871.
35. Lu, W.; Hu, H. T.; Li, Y. X.; Ganguly, R.; Kinjo, R. *J. Am. Chem. Soc.* **2016,** *138*, 6650-6661.
36. Braunschweig, H.; Chiu, C. W.; Radacki, K.; Kupfer, T. *Angew. Chem., Int. Ed.* **2010,** *49*, 2041-2044.
37. Braunschweig, H.; Burzler, M.; Dewhurst, R. D.; Radacki, K. *Angew. Chem., Int. Ed.* **2008,** *47*, 5650-5653.
38. Braunschweig, H.; Dewhurst, R. D.; Pentecost, L.; Radacki, K.; Vargas, A.; Ye, Q. *Angew. Chem., Int. Ed.* **2016,** *55*, 436-440.
39. Kinjo, R.; Donnadieu, B.; Celik, M. A.; Frenking, G.; Bertrand, G. *Science* **2011,** *333*, 610-613.
40. Ruiz, D. A.; Melaimi, M.; Bertrand, G. *Chem. Commun.* **2014,** *50*, 7837-7839.
41. Kong, L. B.; Li, Y. X.; Ganguly, R.; Vidovic, D.; Kinjo, R. *Angew. Chem., Int. Ed.* **2014,** *53*, 9280-9283.
42. Kong, L. B.; Ganguly, R.; Li, Y. X.; Kinjo, R. *Chem. Sci.* **2015,** *6*, 2893-2902.
43. Wu, D.; Kong, L. B.; Li, Y. X.; Ganguly, R.; Kinjo, R. *Nature Commun.* **2015,** *6*, 7340.
44. Imamoto, T.; Hikosaka, T. *J. Org. Chem.* **1994,** *59*, 6753-6759.
45. Kong, L. B.; Lu, W.; Li, Y. X.; Ganguly, R.; Kinjo, R. *Inorg. Chem.* **2017,** *56*, 5586-5593.
46. Monot, J.; Solovyev, A.; Bonin-Dubarle, H.; Derat, E.; Curran, D. P.; Robert, M.; Fensterbank, L.; Malacria, M.; Lacote, E. *Angew. Chem., Int. Ed.* **2010,** *49*, 9166-9169.
47. Ruiz, D. A.; Ung, G.; Melaimi, M.; Bertrand, G. *Angew. Chem., Int. Ed.* **2013,** *52*, 7590-7592.
48. Bernhardt, E.; Bernhardt-Pitchougina, V.; Willner, H.; Ignatiev, N. *Angew. Chem., Int. Ed.* **2011,** *50*, 12085-12088.
49. Landmann, J.; Sprenger, J. A. P.; Bertermann, R.; Ignat'ev, N.; Bernhardt-Pitchougina, V.; Bernhardt, E.; Willner, H.; Finze, M. *Chem. Commun.* **2015,** *51*, 4989-4992.
50. Landmann, J.; Hennig, P. T.; Ignat'ev, N. V.; Finze, M. *Chem. Sci.* **2017,** *8*, 5962-5968.

51. Landmann, J.; Keppner, F.; Hofmann, D. B.; Sprenger, J. A. P.; Haring, M.; Zottnick, S. H.; Muller-Buschbaum, K.; Ignat'ev, N. V.; Finze, M. *Angew. Chem., Int. Ed.* **2017,** *56*, 2795-2799.
52. Gao, M.; Thorpe, S. B.; Kleeberg, C.; Slebodnick, C.; Marder, T. B.; Santos, W. L. *J. Org. Chem.* **2011,** *76*, 3997-4007.
53. Thorpe, S. B.; Guo, X.; Santos, W. L. *Chem. Commun.* **2011,** *47*, 424-426.
54. Gao, M.; Thorpe, S. B.; Santos, W. L. *Organic Lett.* **2009,** *11*, 3478-3481.
55. Gulyas, H.; Bonet, A.; Pubill-Ulldemolins, C.; Sole, C.; Cid, J.; Fernandez, E. *Pure Appl. Chem.* **2012,** *84*, 2219-2231.
56. Cid, J.; Gulyas, H.; Carbo, J. J.; Fernandez, E. *Chem. Soc. Rev.* **2012,** *41*, 3558-3570.
57. Pietsch, S.; Neeve, E. C.; Apperley, D. C.; Bertermann, R.; Mo, F. Y.; Qiu, D.; Cheung, M. S.; Dang, L.; Wang, J. B.; Radius, U.; Lin, Z. Y.; Kleeberg, C.; Marder, T. B. *Chem. Eur. J.* **2015,** *21*, 7082-7098.
58. Dewhurst, R. D.; Neeve, E. C.; Braunschweig, H.; Marder, T. B. *Chem. Commun.* **2015,** *51*, 9594-9607.
59. Neeve, E. C.; Geier, S. J.; Mkhalid, I. A. I.; Westcott, S. A.; Marder, T. B. *Chem. Rev.* **2016,** *116*, 9091-9161.
60. Lee, K. S.; Zhugralin, A. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2009,** *131*, 7253.
61. Zheng, J. H.; Li, Z. H.; Wang, H. D. *Chem. Sci.* **2018,** *9*, 1433-1438.
62. Pecharman, A. F.; Colebatch, A. L.; Hill, M. S.; McMullin, C. L.; Mahon, M. F.; Weetman, C. *Nature Commun.* **2017,** *8*, 15022.
63. Pécharman, A.-F.; Hill, M. S.; Mahon, M. F. *Dalton Trans.* **2018,** *47*, 6.
64. Pecharman, A. F.; Hill, M. S.; McMullin, C. L.; Mahon, M. F. *Angew. Chem., Int. Ed.* **2017,** *56*, 16363-16366.
65. Dove, A. P.; Gibson, V. C.; Hormnirun, P.; Marshall, E. L.; Segal, J. A.; White, A. J. P.; Williams, D. J. *Dalton Trans.* **2003**, 3088-3097.
66. Gilman, H.; Brown, R. E. *J. Am. Chem. Soc.* **1930,** *52*, 1128-1131.
67. Hou, Z. M.; Jia, X. S.; Fujita, A.; Tezuka, H.; Yamazaki, H.; Wakatsuki, Y. *Chem. Eur. J.* **2000,** *6*, 2994-3005.
68. Lalrempuia, R.; Stasch, A.; Jones, C. *Chem. Sci.* **2013,** *4*, 4383-4388.
69. Bonyhady, S. J.; Jones, C.; Nembenna, S.; Stasch, A.; Edwards, A. J.; McIntyre, G. J. *Chem. Eur. J.* **2010,** *16*, 938-955.
70. Yang, Y.; Anker, M. D.; Fang, J.; Mahon, M. F.; Maron, L.; Weetman, C.; Hill, M. S. *Chem. Sci.* **2017,** *8*, 3529-3537.
71. Anker, M. D.; Kefalidis, C. E.; Yang, Y.; Fang, J.; Hill, M. S.; Mahon, M. F.; Maron, L. *J. Am. Chem. Soc.* **2017,** *139*, 10036-10054.